IMPROVED METHODS AND DEVICES FOR IDENTIFYING, SENSING AND TRACKING OBJECTS OVER A SURFACE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to improvements in identifying, sensing, and tracking of objects in predefined spaces by electromagnetic means.

2. Background and Prior Art

There exists a great and increasing need to identify and to automatically detect the presence, orientation and movement of objects in a predefined area. Such objects can include a wide range of animate and inanimate things, such as people's hands, pill bottles, tools, packages, toys, and many more. The applications for such automatic object detection and identification are numerous, including detecting a person's activity over a work surface or interactive display; monitoring the inventory or theft of products on a retail store shelf; locating and aligning parts for robotic assembly in manufacture; and recreational games or toys relying upon placement and movement of objects, to name a few.

One common method of identifying and tracking objects employs a visible "tag" or target marking that is affixed to the desired object and uses a computer vision tracking system to monitor the object. US Patent Nos. 6301763, 5828770, and 4672562, incorporated herein by reference, disclose various machine vision methods for identifying and tracking the 3D movement of objects. While the low cost of such optical tags and markers is an attractive feature, the cost of the camera and vision system is not sufficiently low for many consumer applications. Additionally, vision-based systems require line-of-sight access between the visible marker and the detector, which is difficult to employ in non-controlled environments and lighting conditions, such as for home or retail applications.

Another method of detecting and tracking objects employs an "active" electronic tag affixed to the object, which contains circuitry for transmitting a radio frequency signal that can be used by the host unit to determine the object's identity, presence, orientation or movement. As an example, US Patent No. 6204764, incorporated herein by reference, discloses a method for identifying and tracking objects such as key cards and folders inside a filing cabinet drawers.

Although radio-frequency tagging methods are robust and do not require line-of-sight, the expense of the electronic circuitry inside these tag makes this approach prohibitive for low-cost applications.

As a means of reducing cost, it is also possible to tag an object with an electromagnetically resonant structure, such as an "LC" resonator having an identifiable and detectable resonant frequency and Q factor. US Patent Nos. 6020849 and 5386219, incorporated herein by reference, provide a method for tracking such tagged objects over a surface using an electronic sensing array of coils or electrodes. This technology is commonly used in digitizing pen tablets and computer automated design (CAD) stylus input devices. While the electromagnetic tags employed in such systems are relatively low cost, the electronic switching circuitry and wiring required to multiplex the signals throughout the sensing array make these systems too costly for simple mass market products such as retail store displays, a home medicine cabinet shelf, or children's toys.

Other methods for identifying objects have also been invented in the field of anti-counterfeiting and authentication. US Patent Nos. 5434917 and 3878367, incorporated herein by reference, disclose methods for identifying and authenticating credit cards through the

use of randomly dispersed embedded magnetic particles that are detected as the credit card is swiped past a specialized scanner. US Patent No. 3519802, incorporated herein by reference, describes a method for electromagnetically marking a credit card through the use of embedded conducting plates; detection circuitry for this invention is not described. US Patent No. 5992601, incorporated herein by reference, discloses an apparatus for identifying and sorting currency that has been tagged with specific patterns of magnetic ink. While such anti-counterfeiting and authentication technologies provide a rudimentary means of identifying objects, the detection means is generally limited to specialized scanning and sorting apparatus with fixed geometries, and not adaptable or scalable to surfaces such as table tops, desks, shelves, retail display fixtures, or game boards. Additionally, these inventions do not provide a means for tracking the position or orientation of objects over a surface.

SUMMARY OF THE INVENTION

The present invention provides a method of identifying objects over a surface and a means for determining the position and orientation of the specified objects with respect to the sensing surface. The present invention combines the low-cost advantage of using vision-based tags (e.g. barcodes) with the versatility and security of electronic tagging methods. Furthermore, the present invention can be easily implemented with a conventional manufacturing process, such as printing or attaching a label, and still achieve the ability to operate via non-optical means, such as through a table-top or through packaging material such as an envelope, plastic casing, or product label.

The present invention entails the use of a reference surface, comprised of an array of electrodes or coils generating electromagnetic radiation having a characteristic frequency of oscillation, typically in the range 1-50 MHz. The objects in proximity to the sensing surface couple electromagnetically to the array of electrodes and coils, which then alters the characteristic frequency of one or more elements in the array. The resulting frequency shifts are thus an indirect measure of the electromagnetic response of the object.

By monitoring the individual frequency shifts among the array elements, one or more objects in proximity to the surface can be sensed.

Changes in the characteristic frequencies of the elements are measured using a threshold detector and frequency counter, both of which can be easily implemented using a low-cost microcontroller, for example. Although changes in the sensing field induced by the object can also be monitored by other standard methods, such as measuring changes in the amplitude or phase of the sensing voltage, the technique of frequency-counting is much more inexpensive, requiring a minimal number of electronic components.

For most applications of this invention, the area of each sensing element (electrode or coil) in the sensing array would typically be in the range of 0.1 square centimeters to 100 square centimeters. A densely-spaced array of small sensing elements provides better lateral resolution; however, larger sensing elements provide a greater detection distance, since they produce probing fields that extend a further distance perpendicular to the array surface. In a given application, a combination of large and small sensing elements can also be used.

In the first embodiment of the present invention, rudimentary identification and detection of each object is accomplished by noting the intrinsic electromagnetic response of the material comprising the object (for example, distinguishing between a plastic box, a metal box, or container of milk). The characteristic electromagnetic properties of the objects can be intrinsic to the object or can be engineered, such as through the use of electrically conductive, magnetic, or dielectric materials applied to the object.

More significantly, for the case of a plurality of objects having similar electromagnetic properties, such as a stack of magnetic-ink-coated paper, this embodiment enables the ability to estimate the *quantity* of objects present. This ability is particularly relevant for inventory-monitoring applications, such as counting the number of greeting cards in each pocket of a display rack, or counting the number of magazines in a vending machine row.

In a preferred embodiment of the present invention, a quantifiable method of object identification is further achieved through the use of electromagnetic markers, such as electrically conductive or magnetic patches, that can be either printed or embedded onto (or into) the object in a specific coded pattern. Given

a known electromagnetic response and spatial distribution of the markers, the object can be uniquely identified and its 2D orientation ascertained. Using a large array with greater surface area, multiple objects can also be detected and identified simultaneously.

The present invention also provides a means for determining the lateral position of a specified object or objects. Given an electrode array that is larger than the size of the objects and/or electromagnetic marker pattern, the position of the object can be determined within a resolution limited by the density and number of electrodes in the array. In general, the sensing elements (electrodes or coils) should be closely spaced in order to increase lateral positioning resolution; however, each sensing element must be sufficiently large to adequately couple electromagnetically to the object over the surface.

The noted method also provides a means to determine the orientation of the object relative to the sensing surface. A non-rotationally symmetric 2-dimensional pattern of markers embedded in the surface of the object facing the sensing surface enables the system to determine the 2D orientation of the object. By affixing or embedding the aforementioned electromagnetic markers to all faces of the object's surface, such that each face is distinguishable from every

other face, it then becomes possible to obtain a simple determination of the object's 3D orientation. By way of example, one application of this technique could be a system or method for determining the orientation of a die in a casino board game.

A further embodiment of the present invention involves the use of a second layer of electrodes that are used to modulate or mask-off portions of the electromagnetic field produced by the sensing array. This "modulation layer" thus enables the surface array of the array to be scanned electronically by activating or "unmasking" only one section of the sensing array at a time. Although it is possible to use a conventional approach to multiplex the radio frequency electronics to the sensing array, the cost of a multiplexer and switches for these radio frequency signals is prohibitive for low-cost applications. Therefore, the a motivation for the masking layer of the present invention is to the lower cost and complexity of the system by providing a means for a single set of radio-frequency electronics (oscillator, frequency counter) to selectively monitor each of the potentially large number of electrodes in the sensing array. In addition, careful control of masking enables the system to have an additional degree of control with which to create a spatial mapping of

the electromagnetic properties of the object. Note that in order to modulate or mask the sensing field, the electrodes in the modulation layer only need to be connected to electrical ground and do not need to carry a radio-frequency signal. Therefore, this embodiment makes it possible to scan the sensing array using simple low-cost electronic switching components.

Finally, in a further embodiment of the present invention, the modulation layer mentioned previously can also be employed to convey digital information to an electronic device that is proximal to the sensing array. It is noted that the operation of the modulation layer to mask or unmask portions of the array inherently produces a two-state amplitude modulation of the sensing field (corresponding to switch open or switch closed). Any electronic device tuned to the particular frequency of the array, such as 13.56 MHz, can readily detect and monitor these amplitude modulations. Thus, by modulating the sensing field in a recognizable time-sequence, the sensing array can convey digital information to the proximal electronic device.

BRIEF DESCRIPTION OF THE DRAWINGS

Features and advantages of the present invention will become apparent to those skilled in the art from the description below, with reference to the following drawing figures, in which:

Figure **1A** is a function block diagram of the basic elements of the object sensing and tracking system;

Figure **1B** shows a sample oscillator circuit that can be used as the oscillator component of the present invention;

Figure **1C** shows an alternate oscillator circuit that can be used as the oscillator component of the present invention;

Figure **2A** illustrates the electromagnetic properties of objects with and without electromagnetic markers, in accordance with alternative embodiments of the present invention;

Figure **2B** is an example of the electromagnetic marker patterns for objects to be sensed and tracked by the present invention;

Figure **3A** is a schematic block diagram of a sensor element of the present invention employing direct connection to the oscillator and capacitive coupling to the object;

Figure **3B** is a schematic block diagram of a sensor element of the present invention employing an inductively-coupled connection to the oscillator and capacitive coupling to the object;

Figure **4A** is a schematic block diagram of a sensor element of the present invention employing direct connection to the oscillator and inductive coupling to the object;

Figure **4B** is a schematic block diagram of a sensor element of the present invention employing an inductively-coupled connection to the oscillator and inductive coupling to the object;

Figure **5A** is a schematic block diagram of an embodiment of the present invention incorporating multiple capacitively-coupled sensor elements and employing a multiplexer switch and a separate oscillator for each sensor;

Figure **6A** is a schematic block diagram of an embodiment of the present invention incorporating multiple inductively-coupled sensor elements and employing a multiplexer switch and separate oscillator for each sensor;

Figure **5B** is a schematic block diagram of an embodiment of the present invention incorporating multiple capacitively-coupled

sensor elements multiplexed to a single oscillator and frequency counter;

Figure **6B** is a schematic block diagram of an embodiment of the present invention incorporating multiple inductively-coupled sensor elements multiplexed to a single oscillator and frequency counter;

Figure **7** is a schematic block diagram of a preferred embodiment of the present invention incorporating multiple capacitively-coupled sensor elements inductively-coupled to a single oscillator;

Figure **8** is a schematic block diagram of a preferred embodiment of the present invention incorporating multiple inductively-coupled sensor elements inductively-coupled to a single oscillator;

Figure **9** is a schematic block diagram of an alternative embodiment of the present invention incorporating multiple capacitively-coupled sensor elements and employing shielding electrodes for masking selected sensing elements;

Figure **10** is a schematic block diagram of an alternative embodiment of the present invention incorporating multiple

inductively-coupled sensor elements and employing shielding electrodes for masking selected sensing elements;

Figure **11** is a schematic block diagram of an embodiment of the present invention employing shielding electrodes and electromagnetic field modulation to communicate with external electronic devices;

Figure **12A** is a version of the object sensing and tracking system using a large array containing many capacitive sensor elements;

Figure **12B** is a version of the object sensing and tracking system using a large array containing many inductive sensor elements;

Figure **13** is a version of the object sensing and tracking system showing how several arrays can be multiplexed together to create multiple sensing zones.

Figure **14** illustrates a sample embodiment of the present invention applied to a children's toy for identifying alphabet tiles.

Figure **15** illustrates a sample embodiment of the present invention applied to a retail store shelf for sensing and tracking objects for the purpose of real-time inventory and security.

DESCRIPTION OF ILLUSTRATED EMBODIMENTS

In Figure **1A**, the basic operation of the electronic object sensing and tracking system **100** is illustrated with a general functional diagram. A fundamental feature of the present invention is the generation of an oscillating electromagnetic signal targeted at objects or potential objects via one or more antenna structures or "sensing elements" **130,** each having a characteristic resonant frequency. External objects in proximity to each sensing element **130** produce a change in the characteristic frequency in accordance to their electromagnetic material properties. Measured changes in the characteristic frequency of one or more sensing elements are then used to determine the presence, identity, and movement of the objects in relation to a predefined surface or surfaces.

Measurement of the characteristic resonant frequencies are accomplished through the use of a comparator or threshold detector **112** that monitors the amplitude or power level of oscillator **120**. As the probing frequency is varied, the change in signal amplitude at resonance triggers the threshold detector **112,** which in turn initiates the frequency counter reading. The frequency counter **110** is also implemented internally using a microcontroller IC chip **150** and thus

enables the relevant frequency shifts to be measured accurately and inexpensively with minimal external components.

The oscillator **120** in Figure **1A** can be implemented using a number of different electronic circuit topologies known in the art, ranging from single-chip solutions to discrete-component oscillator circuits. Relevant types of electronically-tunable oscillators include, but are not limited to: op-amp oscillators, discrete-component LC oscillators, single-chip VCOs (Voltage-controlled oscillators), Phase-Locked Loop (PLL) synthesizers, and Direct Digital Synthesis (DDS) ICs. Most relevant for low-cost implementations are single-chip or discrete component Voltage Controlled Oscillators (VCO) that can be tuned electronically using a control voltage. This control voltage can also be implemented very inexpensively with a low-cost microcontroller, either by low-pass filtering a Pulse Width Modulated (PWM) output or by incremental charging and discharging of an external capacitor using a sequence of digital pulses.

In the low-frequency range (less than 1 MHz), op-amp based VCOs or single chip CMOS VCOs (such as the CMOS 555) are most cost effective; but at higher frequencies, discrete-component VCO's are generally most appropriate. Figure **1B** and Figure **1C** illustrate the

two single-transistor circuit topologies most relevant for low-cost implementation: the emitter-coupled version of the Colpitts oscillator **170** with inductive feedback (Figure **1B**); and the emitter-coupled version of the Hartley oscillator **180** with capacitive feedback (Figure **1C**). In both cases, the characteristic frequency (in Hz) of each circuit is approximately given by $f = \frac{1}{2\pi\sqrt{LC}}$ as determined by resonators **175** and **185** and modulated by the additional tuning capacitance of the varactor diodes. Equivalent circuits employing FETs (Field Effect Transistors) instead of BJTs (Bipolar Junction Transistors) can also be used and are preferred for low-power applications.

As a system for sensing and tracking objects, the present invention can be implemented using a wide variety of oscillator types, including those mentioned previously. In the simplest implementations, such as in the case of a discrete-component Hartley or Colpitts oscillator, the resonant sensing element is an integral part of the oscillator circuit itself, and in this case it is difficult to define a sensing element separately from the oscillator. However, for the purpose of clarity and generality, it is most useful to describe the present invention in terms of an oscillator and one or more "sensing elements", comprised of an inductor-capacitor network (typically

planar electrode and coils). In the remaining figures and ensuing descriptions, the various embodiments of the present invention are thus illustrated as an oscillator, a frequency counter, and an external inductor-capacitor network.

Figure **2A** explains the properties of the object(s) being sensed by the present invention. The changes in the characteristic frequency are a function of object's material characteristics: electrical conductivity (σ_1), dielectric permittivity (ε_1) and magnetic permeability (μ_1). In order to be detected, at least one of these properties must be significantly different from that of the surrounding medium (usually air) with electromagnetic properties σ_0, ε_0, and μ_0. In general, the electrical conductivity produces a positive frequency shift, while dielectric materials and magnetically permeable materials produce a negative frequency shift. The magnitude of the frequency shift is determined by the distance between the object and the sensing elements, but in practice, the objects are placed at a fixed distance from the sensing elements, (for example, resting on the sensing surface), which gives reproducible and recognizable signals based on the material properties.

In a further aspect of the present invention, the detection of the objects can be enhanced through the use of electromagnetic markers **206**. In the preferred embodiment, the markers are comprised of materials having easily distinguishable electromagnetic properties σ_2, ε_2, and μ_2, and may be in the form of a attached label, printed coating, or embedded regions of material. Since the present invention does not require line-of-sight optical access to the markers, the markers may also be embedded under the surface or into the object for aesthetic purposes. Figure **2A** shows an unmarked object **202** as well as a marked object **204**.

Figure **2B** illustrates how the spatial pattern of the electromagnetic markings can be used as a means of uniquely identifying the objects. By employing an array of sensing elements, the objects may be distinguished by properly chosen unique marker patterns and the resulting electromagnetic field distortions produced. Figure **2B** shows several examples of marker patterns used with a small sample of different object types (**210**, **220**, **230**, **240**, **250** and **260**) which can be monitored by the present invention.

The radio-frequency electromagnetic field generated by the sensing elements can be coupled to the external objects in two ways,

capacitive coupling and inductive coupling, as determined by the geometry of the sensing elements. Although alternating electromagnetic fields necessarily contain both electric and magnetic field components, planar electrode patches contain locally uniform regions of electric field that enhances capacitive coupling and is suited for probing an object's dielectric properties. Conversely, the locally uniform magnetic field produced by coil geometries is best suited for inductive coupling and probing an object's magnetic properties.

Figure **3A** and Figure **3B** illustrate capacitively-coupled versions **300, 302** of the object sensing and tracking system, for capacitively coupling the electromagnetic field to the object **160**. The system **300** includes the aforementioned frequency counter **110** and oscillator component **120**. The figures also illustrate the resonator portion of oscillator **120**, shown here more explicitly as elements **370** and **380**, respectively, along with capacitively-coupled antenna element **250**. Figure **3A** illustrates direct coupling between the oscillator and resonator elements. Figure **3B** illustrates inductive coupling between the oscillator and resonator elements, which eliminates the need for a physical connection between the oscillator and resonator elements.

The systems **400, 402** in Figure **4A** and Figure **4B** are similar to the systems **300, 302** in Figure **3A** and Figure **3B**, except that inductive coupling to the object **160** is employed (via element **470**) as the primary sensing means.

A method for connecting a single frequency counter (and its associated electronics) to a plurality of sensor elements is illustrated in Figure **5A**. A plurality of capacitively-coupled sensing elements (**582, 584, 586**) are selectively activated to detect and monitor an object. Each sensing element is connected to a dedicated oscillator (**522, 524, 526**). A switch (or multiplexer) **515** under the direction of the microcontroller (not shown) determines which sensor element (or elements) is active and enables the sensing array to be serially scanned.

Figure **6A** depicts an alternate embodiment (**600**) of the present invention, in which the capacitive sensor elements are replaced by inductive sensor elements (represented by the numbers **672, 674** and **676**) for inductive coupling to the object. Elements **615, 622, 624** and **626** are analogous to the following Figure **5A** elements, respectively: **515, 522, 524** and **526**.

Alternative methods for implementing an array of sensing elements is shown in Figure **5B** and Figure **6B**. The functions of the circuits in Figures **5B** and **6B** are identical to the functions of the circuits of Figures **5A** and **6A**, respectively. However, rather than having several dedicated oscillators, the circuits in Figures **5B** and **6B** contain only a single oscillator that is multiplexed to each of the sensor elements in the array. All of the system components in Figures **5B** and **6B** are analogous to their counterparts in Figures **5A** and **6A**.

A preferred method for implementing a plurality of sensing elements is illustrated in Figure **7** and Figure **8**. In this embodiment, the individual sensor elements in the array are inductively coupled to the oscillator **720** via a single coil (depicted as **762**, **764**, and **766**). This embodiment greatly reduces the amount of wiring and circuitry needed to implement multiple sensing elements using a single oscillator and frequency counter. By using sensor elements with distinct resonant frequencies, each element can be individually monitored and distinguished. In order to prevent possible a overlap in the resonant frequencies between several sensor elements during operation, the resonant frequencies of the sensor elements are selected to be at frequency intervals larger than the frequency shift (typically

10 KHz - 100 KHz) caused by the interaction with the external object **160** over surface **702**. A frequency spacing of 500 KHz – 2000 KHz for the sensor elements is adequate for most applications.

Another embodiment of the present invention is illustrated in Figures **9** and **10**. As an alternative to having individual spatially-resolved sensing elements, these embodiments employ a layer of shield or guard electrodes (**992**, **994**, **996**, and **998**) as modulators for selectively enabling or disabling ("masking") portions of the sensing field. When a given shield electrode is electrically connected to ground, it then functions as an electrical shield that attenuates and effectively disables the portion of the sensing field corresponding to one or more of the sensor electrodes immediately below it. Careful control of masking by the microprocessor enables the system to have an additional degree of control for creating a spatial mapping of the electromagnetic properties of the object. Compared to other embodiments of the present invention, this embodiment is particularly useful for implementing a closely-packed sensing array with high spatial resolution, where there is insufficient surface area to implement individual resonator elements (as in Figures **7** and **8**).

Figure **9** illustrates three capacitively-coupled sensor elements **982**, **984**, and **986** connected to oscillator **920** and a frequency counter **110** for measuring characteristic frequency changes. The sensor elements **982**, **984**, and **986** are selectively masked by the shielding electrodes **992**, **994**, **996**, and **998** under the control of a control logic circuit **902** (a subset of the microprocessor or microcontroller) and a switch or multiplexer **915**. Figure **10** illustrates a similar system but employing inductive coupling to the external object via coil portions **1072**, **1074**, and **1076**.

In a further alternate embodiment (**1100**) of the present invention shown in Figure **11**, it is illustrated how the same masking electrodes and field modulation described above can be used to communicate information to an external device or appliance. In particular, the electromagnetic sensing field is modulated in a data pattern to communicate information to external wireless electronic devices (e.g., handheld PCs, PDAs, personal communication devices, RFID tag readers, cellular telephones, and hand-held data input devices). Along with an oscillator **1120**, an antenna element **1180**, and counter/detection circuitry **1104**, the circuit **1102** also contains data control **1106** responsible for controlling a switch **1115** and a

shielding electrode **1190**. The data control **1106** causes the switch to modulate the electromagnetic field according to the appropriate data pattern that can be received by the external wireless communication device. The data control **1106** and switch **1115** can be electronically identical to control logic **902** and switch **915** shown in Figures **9** and **10**, but have been renamed in Figure **11** simply to emphasize their alternate functionality.

For extending the capabilities of the present invention to larger surface areas, it is possible and often desirable to combine several smaller sensing arrays into a larger system. Capacitively-coupled arrays (Figure **12A**) and inductively-coupled arrays (Figure **12B**) can thus be treated as "sub-arrays" and multiplexed together to form a contiguous sensing zone, as shown in system **1300** of Figure **13** in accordance to an alternative embodiment of the present invention. Along with sensing electronics **1350**, the embodiment **1300** also contains several sub-arrays (represented by the numbers **1302, 1304,** and **1306**) connected by signal buses **1314, 1316** and **1318**, and a multiplexer **1340**.

Figure **14** illustrates an application of the present invention to a children's letter toy consisting of four sensing zones that can

electronically identify letter tiles (e.g. **1410, 1420, 1430, 1440**). Each sensing zone consists of a small sub-array of resonant elements **1485** that are inductively-coupled to the oscillator via coil **1480**. An inexpensive electronic marker **1435** in the form of a metal foil label or printed conducting ink pattern is affixed to each letter tile in a unique geometric pattern designed to overlap or partially overlap one or more sensing elements. Placement of a letter tile on any one of the sensing zones causes a shift in one or more resonant frequencies of the sensor elements **1485**, thus enabling the letter tile to be uniquely identified. By increasing the number of resonant elements in each sub-array, a larger number of electronic marker patterns can be distinguished. This additional information can be employed to measure 2D orientation as well as to recognize a larger number of tiles.

Figure **15** illustrates an embodiment of the present invention applied to retail inventory-monitoring and security. A display fixture **1510** designed to hold music CDs **1530** (or equivalently, greeting cards, DVD's, books or magazines) is shown in Figure **15** having multiple sensing zones (sub-arrays) **1580** tailored to the specific shelf size and spacing for holding the music CDs. Electronic markers (e.g. foil labels, electrically conductive ink, magnetically-permeable ink)

affixed or printed to the music CD cases enable a basic level of identification (on the order of 10-20 bits of information). Most importantly, however, the present invention enables the system to electronically monitor the presence and movement of the products on display. This, in turn, can enable a wide variety of applications such as automatic re-ordering for product shelves that are empty and tracking activity on the shelf level for security applications and integration with a automated store surveillance cameras.

While this invention has been described in terms of several embodiments and specific examples, there are alterations, permutations, and equivalents which fall within the scope of this invention and protection granted by this Letters Patent. It is therefore intended that the following appended claims be interpreted as including all such alterations, permutations, and equivalents as fall within the true spirit of the present invention.